

Heart Rhythm Disorders

Cost Advantage of Dual-Chamber Versus Single-Chamber Cardioverter-Defibrillator Implantation

Zachary Goldberger, MD,* Brian Elbel, MPH,† Craig A. McPherson, MD, FACC,*
A. David Paltiel, PhD,† Rachel Lampert, MD, FACC*

New Haven, Connecticut

OBJECTIVES	The purpose of this study was to determine the least expensive strategy for device selection in patients receiving implantable cardioverter-defibrillators (ICDs).
BACKGROUND	Device cost for a single-chamber ICD is less than an atrioventricular (dual-chamber) ICD (AV-ICD); however, some patients without clinical need for AV-ICD at implantation might require a later upgrade, potentially offsetting the initial cost advantage of the single-chamber device.
METHODS	Decision analysis was used to estimate expected resource utilization costs of three alternative implantation strategies: 1) single-chamber device in all, with later upgrade to AV-ICD if needed; 2) initial implantation of an AV-ICD in all; and 3) targeted device selection on the basis of results of electrophysiologic testing (presence or absence of induced bradyarrhythmias or atrial arrhythmias). Clinical base estimates were obtained from retrospective review of all patients receiving ICDs between June 1997 and July 2001 at a single university hospital. Economic inputs were collected from national and single-center sources.
RESULTS	In patients without other indications for electrophysiologic study (EPS), the expected per-person cost was least with the strategy of universal initial AV-ICD implantation (\$36,232) compared with initial single-chamber ICD/upgrade as needed (\$39,230) or EPS-guided selection (\$41,130). Sensitivity analyses demonstrated that universal AV-ICD implantation remained least expensive with upgrade rates as low as 10%. At a 5% upgrade rate, AV-ICD remained cheapest if the device cost-differential narrowed to \$1,568. For patients undergoing EPS for risk assessment, EP-guided selection was least expensive.
CONCLUSIONS	The strategy of universal AV-ICD implantation, which provides the benefits of dual-chamber capability while obviating any potential need for future upgrade, is the least costly strategy for most patient populations receiving ICDs. (J Am Coll Cardiol 2005;46:850–7) © 2005 by the American College of Cardiology Foundation

The implantable cardioverter-defibrillator (ICD) is the standard of care for patients at risk for sudden cardiac death (1–4). The atrioventricular (dual-chamber) ICD (AV-ICD), approved by the Food and Drug Administration (FDA) in 1997, is indicated for patients who are at risk for ventricular tachyarrhythmias and also in need of pacing for bradycardia (5,6). Of ICD recipients, 15% to 20% require antibradycardia pacing, owing to intrinsic sinus node dysfunction or conduction system disease, or use of medications with negative chronotropic properties (7,8). Furthermore, patients with atrial tachyarrhythmias might benefit from the arrhythmia detection capability afforded by the atrial lead in the AV-ICD, which might help prevent delivery of inappropriate shocks for supraventricular arrhythmias (5,9,10). Currently, approximately 40% to 51% of ICDs implanted in the U.S. are dual-chamber devices (industry data, Medtronic Inc., Minneapolis, Minnesota, and Guidant Corp., St. Paul, Minnesota).

Although many patients demonstrate the need for dual-chamber capabilities at the time of initial ICD implantation,

others develop sinus node dysfunction, AV nodal conduction disease, or atrial arrhythmias later, thereby necessitating upgrade to a dual-chamber device. Upgrades entail repeated surgical procedures, with rare, although serious complications such as infection, which may be more common with re-operation than with initial implants (11,12). In addition, the cost of a new device, along with the cost of a repeated procedure, makes avoidance of upgrades highly preferable.

For patients without an apparent need for dual-chamber capability at the time of implant, the optimal approach to initial device selection—single- versus dual-chamber—has not been investigated. The most common approach in these patients is to implant a single-chamber device and subsequently upgrade to an AV-ICD should the need arise. A second approach would be to implant AV-ICDs initially in all patients, regardless of clinical need for dual-chamber capability at the time of implant. Universal implantation of an AV-ICD is a potentially attractive strategy, because it might minimize inappropriate ICD shocks for supraventricular arrhythmias while concomitantly avoiding the need for later upgrade from a single-chamber device should bradyarrhythmias develop. A third approach would be to use information on potential subclinical sinus node or AV node dysfunction or predisposition to atrial arrhythmias gained

From the Schools of *Medicine and †Epidemiology and Public Health, Yale University, New Haven, Connecticut.

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Abbreviations and Acronyms

ACC	= American College of Cardiology
AHA	= American Heart Association
AV-ICD	= atrioventricular (dual-chamber) implantable cardioverter-defibrillator
AVID	= Anti-arrhythmics Versus Implantable Defibrillators trial
CHF	= congestive heart failure
DAVID	= Dual-Chamber and VVI Implantable Defibrillator trial
EPS	= electrophysiology/electrophysiologic study
ICD	= implantable cardioverter-defibrillator
MADIT	= Multicenter Automatic Defibrillator Implantation Trial
MUSTT	= Multicenter UnSustained Tachycardia Trial
NASPE	= North American Society of Pacing and Electrophysiology
SCD-HeFT	= Sudden Cardiac Death in Heart Failure Trial

from electrophysiologic study (EPS) as a means of predicting the future need for dual-chamber capabilities, thus employing electrophysiologic-guided assessment as a determinant of device selection. To determine which of these three strategies for device selection in patients requiring ICD therapy would be least costly, we constructed a decision-analysis model with retrospective data from our institution on device usage.

METHODS

Study design. We developed a decision analytic model to estimate the economic costs of three alternative implantation strategies in ICD recipients who do not demonstrate the need for a dual-chamber device at time of implant: 1) initial implantation of a single-chamber device in all patients with later upgrade to an AV-ICD as clinically needed; 2) initial implantation of an AV-ICD in all patients; and 3) targeted initial device selection on the basis of the results of electrophysiologic testing. The decision tree in Figure 1 depicts these three choices, their associated costs, and their downstream clinical consequences. The choice of a single-chamber ICD carries the risk that patients will require subsequent upgrades to an AV-ICD. By contrast, the choice of an AV-ICD removes this risk entirely. With electrophysiologic-guided device selection, the upgrade risk might be potentially reduced but not entirely eliminated.

Base estimates of outcome probabilities were determined with clinical data obtained from retrospective review of data from the Yale University School of Medicine electrophysiology practice. Economic inputs for the analysis (including device costs, procedure and hospital costs, and professional fees) were collected from national and local sources. All monetary outcomes were reported in 2002 U.S. dollars. The analysis conforms to the reference case recommendations of the U.S. Panel on Cost-Effectiveness in Health and Med-

icine (13). This study was approved by the Yale Human Investigational Committee.

Determination of base estimates. We used data from the Yale electrophysiology experience to determine base estimates for the probability of upgrade to AV-ICD after implantation of a single-chamber ICD without EPS, the probability of abnormal EPS, and the probability of upgrade if electrophysiologic-guided selection is used (i.e., the predictive accuracy of EPS).

The Yale University Electrophysiology Database and patient charts were reviewed to identify all patients who received an ICD in the four years after FDA approval of the AV-ICD in June 1997 and to determine whether subsequent upgrade was performed. Patients with permanent atrial fibrillation, who had failed attempts at maintenance of sinus rhythm and for whom no further attempts at maintenance of sinus rhythm were planned, were excluded (n = 33), because these patients could not benefit from an atrial lead at implantation nor develop indication of benefit from an atrial lead in follow-up. The remaining 453 patients who received either a single- or dual-chamber ICD between June 1997 and July 2001 were included in the analysis.

After the approval of the AV-ICD by the FDA in June 1997, Yale electrophysiologists empirically instituted a strategy to implant the AV-ICD in two groups of patients. First, patients with a clinical need for dual-chamber pacing or sensing, similar to those later described in the American College of Cardiology/American Heart Association /North American Society of Pacing and Electrophysiology (ACC/AHA/NASPE) 2002 Guideline Update for Implantation of Cardiac Pacemakers and Antiarrhythmia Devices (5), received an AV-ICD. Second, those with abnormal sinoatrial function or impaired atrioventricular nodal conduction, or

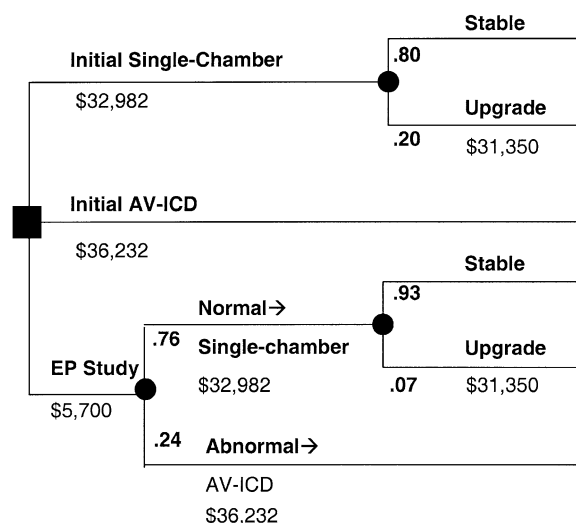


Figure 1. Decision tree. The square node on the left represents a choice among the three strategies under examination. The circles represent chance nodes at each of the associated downstream probabilities for points of uncertainty. The costs listed are the non-cumulative costs associated with that particular point in the decision analytic model. AV-ICD = atrioventricular (dual-chamber) implantable cardioverter-defibrillator; EP = electrophysiologic.

induced atrial arrhythmias at invasive EPS, performed pre-operatively in all patients according to published methods (14), received the atrioventricular device. Specific criteria included: corrected sinus node recovery time ≥ 540 ms, sinoatrial conduction time ≥ 230 ms or His ventricular interval ≥ 70 ms, or induction of an atrial arrhythmia. Patients without either clinical or electrophysiologic criteria for AV-ICD implantation received a single-chamber ICD.

Upgrade to AV-ICD was performed if indications for the dual-chamber device developed at a time after initial implantation; indications included: 1) symptomatic bradyarrhythmias with symptoms of pacemaker syndrome during VVIR (ventricular rate responsive) pacing (weakness, exercise intolerance or pre-syncope, similar to those specified in the Mode Selection Trial [MOST] as qualifying for cross-over to dual-chamber mode) (15); 2) inappropriate shocks for supraventricular arrhythmias; or 3) symptomatic congestive heart failure (CHF) with bradycardia or prolonged PR interval. At the time of this study, guidelines for AV-ICD implantation did not exist and the need for upgrade was determined on the basis of presence of these criteria. Subsequently published series (12,16) and more recent 2002 ACC/AHA/NASPE guidelines (5) demonstrate that the first two of these criteria for a dual-chamber device remain widely accepted. The probability of upgrade from a single-chamber to an AV-ICD device in patients with a normal EPS (who had thus received an initial single-chamber ICD) was determined in patients receiving an ICD between June 1997 and July 2001.

Because all patients who received an ICD at our center during these years underwent EPS, and all those with abnormal findings received AV-ICDs, we determined the probability of upgrade without EPS via extrapolation. We first determined the positive predictive accuracy of the EPS, defined as the percentage of those with abnormal EPS who then underwent later upgrade, in a separate population of 54 patients who received single-chamber devices between January 1996 and June 1997 (before the availability of the AV-ICD). Among these patients, 20 had an abnormal EPS, 12 of whom required upgrade (significantly greater than those with normal EPS [11 of 34, 32%, $p < 0.05$]). Thus, the positive predictive accuracy of EPS was 60% (12 of 20). We then extrapolated the probability of upgrade for our initial population in all patients without clinical indication for an AV-ICD and without prior EPS, as shown in Figure 2. Total upgrades, in the numerator, was based on the number of actual upgrades in those receiving a single-chamber device (normal EPS) plus the number of expected upgrades in those who had received an AV-ICD by electrophysiologic criteria, on the basis of the positive predictive accuracy of the EPS. Total number of patients without clinical indication for EPS, in the denominator, included those who received a single-chamber ICD after a normal EPS and those who received an AV-ICD solely on the basis of an abnormal EPS.

(Total upgrades)			
Actual upgrades, Single-chamber/ Normal EPS		Expected upgrades,* AV-ICD/Abnormal EPS	
15	+	38	= 20%
207	+	64	
Received Single-chamber/ Normal EPS		Received AV-ICD/ Abnormal EPS	
(All those without clinical indication AV-ICD)			

Figure 2. Extrapolation of upgrade rate for patients not undergoing electrophysiologic study (EPS). *Expected upgrade rate, determined on the basis of positive predictive value of the EPS (see Methods for details). AV-ICD = atrioventricular (dual-chamber) implantable cardioverter-defibrillator.

Sources for economic data. Economic data analyzed was chosen to reflect resource use and included a combination of actual costs to the hospital and professional fees, used as a surrogate for cost for this aspect of resource use. Economic data, listed in Table 1, were derived from three sources. Device costs to the hospital were national averages formed on the basis of a survey taken in 2002 from 2,100 members of the Cardiovascular Roundtable of the Advisory Board Company, a national health-practice consortium of over 2,000 health care systems. Other hospital costs (overnight stay and operating room costs) were averages of actual operational costs for Yale-New Haven Hospital in 2002 (e.g., wages, supplies, averaged for a per-person overnight stay on a cardiac-monitored floor), calculated by the Yale-New Haven Hospital internal accounting system. Professional fees were actual 2002 fees charged by Yale faculty practice electrophysiologists and anesthesiologists.

Sensitivity analyses. Sensitivity analysis was first conducted on the target population assumption. We first performed an analysis for a population of patients without other clinical indications for EPS (i.e., meeting criteria for ICD implantation defined in the Anti-arrhythmics Versus Implantable Defibrillators [AVID] trial) (1). Subsequently, we analyzed a population of patients undergoing EPS for risk-stratification to determine the need for ICD (i.e., meeting criteria for ICD implantation defined in the primary-prevention Multicenter UnSustained Tachycardia Trial [MUSTT] and Multicenter Automatic Defibrillator Implantation Trial [MADIT I]) (2,3). For this group, information gained from the EPS could be used to guide device selection at no additional cost.

We also conducted sensitivity analyses to test the robustness of our conclusions to uncertainty in the underlying input data. Specifically, we explored the impact of varying the following input parameters over a range of values: 1) the proportion of patients requiring an upgrade to an AV-ICD after the initial implantation of single-chamber ICD; 2) the cost differential between the dual- and single-chamber devices; 3) the timing of upgrade (i.e., cost depreciation);

Table 1. Economic Inputs

	Single-Chamber ICD (Initial Implantation)	AV-ICD (Initial Implantation)	Upgrade	Atrial Lead Repositioning	EPS
System (including device and leads)	\$22,000	\$25,250	\$19,350		
Other hospital costs					
Operating room	\$2,500	\$2,500	\$2,500	\$2,500	
Hospital stay	\$867	\$867	\$867	\$867	
EPS procedure					\$2,700
Professional fees					
Electrophysiologist	\$6,575	\$6,575	\$7,593	\$1,667	\$3,000
Anesthesiologist	\$1,040	\$1,040	\$1,040	\$1,040	
Total	\$32,982	\$36,232	\$31,350	\$6,074	\$5,700

Derivation of costs and fees is described in the text. Costs in 2002 dollars.

AV-ICD = atrioventricular (dual-chamber) implantable cardioverter-defibrillator; EPS = electrophysiologic study.

and 4) the non-device costs associated with the procedure. Because ranges of input data are not available in the published literature, we varied each parameter over plausible ranges.

We also conducted a sensitivity analysis incorporating the potential for atrial lead dislodgement, requiring lead repositioning, with a base estimate of 4% as described in published reports (16,17).

Statistical analysis. Comparisons of upgrade rates between patients with normal versus abnormal EPS, and between patients receiving ICDs for primary versus secondary prophylaxis, were performed with chi-square analysis with JMP 5.0 software (SAS Institute, Cary, North Carolina).

RESULTS

Study population. The population from which the base estimates were derived was 79% male (mean age 65 ± 13 years) and 71% had coronary artery disease. Indications for ICD included sustained ventricular tachycardia in 27%, ventricular fibrillation in 18%, and primary sudden death prophylaxis in 55%. There were no differences in devices received or later upgrades on the basis of any demographic or clinical variable. Devices implanted and their indications in the 453 patients who received an ICD between June 1997 and July 2001 are shown in Figure 3. Among the 271 patients without clinical indication for dual-chamber pacing at implantation, the probability of an abnormal EPS was 24%.

Base estimates. PROBABILITY OF UPGRADE—NORMAL EPS. Of the 207 patients who had no clinical indications for dual-chamber pacing and a normal EPS, who therefore received single-chamber ICDs, the probability of upgrade to AV-ICD was 7%. Indications for upgrade in these 15 patients are shown in Figure 3 and included symptomatic bradyarrhythmias in 6 patients (2 with complete heart block, 4 with sick sinus syndrome), inappropriate shocks for paroxysmal atrial fibrillation in four patients, and CHF with bradycardia or prolonged PR interval in 5 patients. There was no difference in the upgrade rate between those receiving an ICD for primary sudden death prophylaxis versus for secondary prophylaxis after a clinical arrhythmia (6.8% vs. 8.6%, respectively, $p = 0.6$).

PROBABILITY OF UPGRADE WITHOUT PERFORMANCE OF EPS. Derivation of the probability of upgrade without performance of EPS is shown in Figure 2. There were 15 actual upgrades among the 207 patients implanted with a single-chamber ICD after a normal EPS. Of the 64 patients with an abnormal EPS (who had thus received an AV-ICD), on the basis of the 60% positive predictive accuracy of EPS as described previously, the expected number of upgrades was 38. On the basis of the extrapolation described in the Methods section, the probability of requiring subsequent AV-ICD upgrade without prior EPS was 20%.

Decision analytic model. PATIENTS WITHOUT OTHER INDICATIONS FOR EPS. As shown in Figure 4, in patients without other indications for electrophysiologic testing, the expected cost was least with the strategy of universal initial AV-ICD implantation, with an expected per-person cost of \$36,232. The strategy of initial single-chamber ICD with AV-ICD upgrade as needed generated an expected per-person cost of \$39,230. The strategy of EPS before implantation was the most expensive option, with an expected per-person cost of \$41,130. Further analysis with an

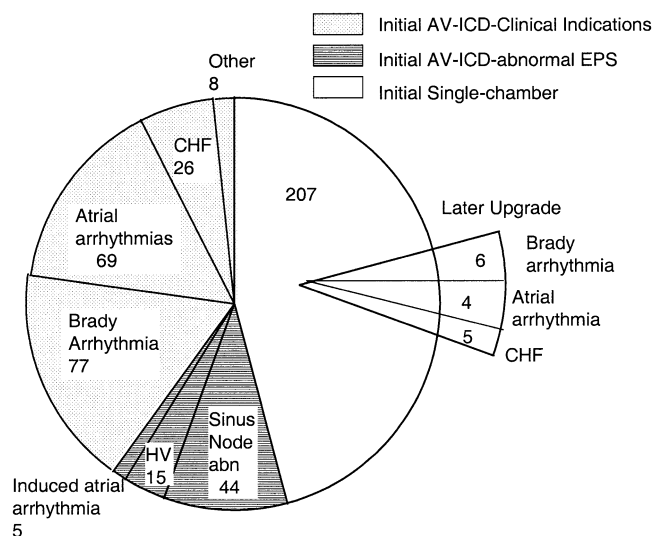


Figure 3. Initial devices received June 1997 and July 2001 and indications. Offset represents upgrades received and indications. Values represent numbers of patients. CHF = congestive heart failure; HV = His ventricular interval; other abbreviations as in Figure 2.

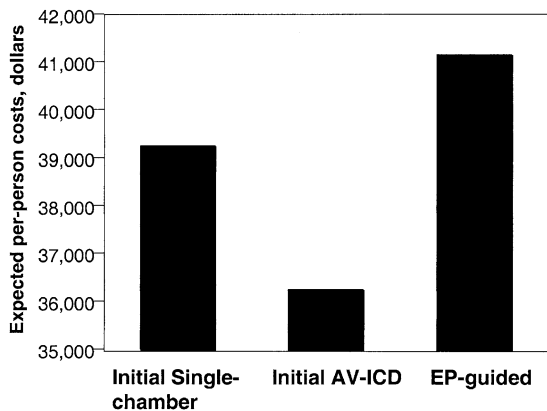


Figure 4. Expected per-person costs of each strategy, initial single-chamber implantation with upgrade as needed, universal dual-chamber implantation (AV-ICD), and use of electrophysiologic study to guide decision (EP-guided).

inflation-adjusted (at an annual rate of 3%) value for the upgrade cost, assuming an average upgrade time of 2.5 years, had no material effect on the cost estimates or rankings between treatment choices.

PATIENTS UNDERGOING EPS FOR RISK ASSESSMENT. Among patients who undergo EPS to determine the need for an ICD implant itself (i.e., MADIT 1 and MUSTT populations), the cost of EPS itself can be excluded from the calculation. For these patients, use of electrophysiologic-guided selection was the least costly strategy. In those with abnormal EPS findings, it is considerably less expensive (\$38,000 vs. \$53,000) to implant AV-ICDs than single-chamber ICDs. For those with normal EPS findings, expected per-person cost was less with the single-chamber (\$34,000 vs. \$38,000).

SENSITIVITY ANALYSIS: UPGRADE RATE. Individual clinicians may vary in their threshold for initial AV-ICD implantation as well as for upgrade, and institutional norms might vary. To reflect these practice variations, we explored upgrade rates ranging from 5% to 35% (baseline assumption = 20%). As illustrated in Figure 5, higher upgrade rates will

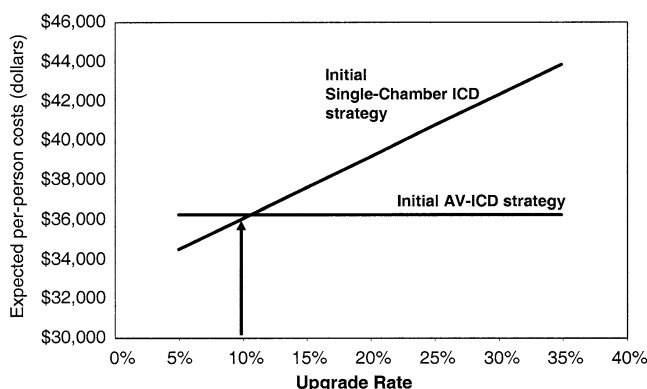


Figure 5. Sensitivity analysis, upgrade rate. Input varied from 5% to 35%, baseline assumption 20%. **Arrow** denotes threshold of indifference. AV-ICD = atrioventricular (dual-chamber) implantable cardioverter-defibrillator.

produce higher costs for the strategy of initially implanting single-chamber devices. At an upgrade rate of 10%, the per-person cost of the initial single-chamber device implantation would be equivalent to the cost of universal AV-ICD implantation. Our finding in favor of an AV-ICD is robust for any upgrade rate assumption greater than this threshold value.

SENSITIVITY ANALYSIS: DEVICE COST DIFFERENTIAL. Upgrade rates at some institutions might be lower than 10%. Therefore, we also evaluated how much the cost-differential would need to narrow for the universal AV-ICD strategy to remain least expensive at an upgrade rate of just 5%. As shown in Figure 6, as the cost differential between the single- and dual-chamber devices narrows, the strategy of implanting the dual-chamber device in all patients increasingly becomes the least expensive option. A cost differential of \$1,568 between the two devices (about one-half the current cost differential) would keep the implantation of an AV-ICD at initial implant the least expensive strategy, even at an upgrade rate as low as 5%.

SENSITIVITY ANALYSIS: TIMING OF UPGRADE. Because the timing of upgrade will impact the long-term cumulative costs of ICD therapy, we also performed a sensitivity analysis varying the timing of upgrade assuming a straight-line depreciation of device value over time, with other variables held constant. Universal AV-ICD implantation remains the least expensive strategy at this upgrade rate, assuming that a mean of at least 52% battery life remains at the time of upgrade.

SENSITIVITY ANALYSIS: NON-DEVICE COSTS. We examined the impact of varying other costs, including professional fees and hospital costs, on the baseline \$3,000 cost advantage of the AV-ICD strategy. As shown in Figure 7, varying non-device cost estimates from 50% to 200% of their original values did not alter the cost advantage of universal AV-ICD implantation.

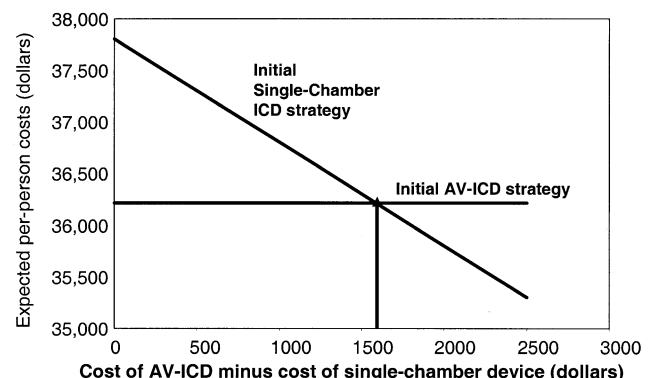


Figure 6. Sensitivity analysis, cost-differential, assuming 5% upgrade rate. Input varied from \$500 to \$3,000, current cost-differential \$32,940. **Arrow** denotes threshold of indifference. AV-ICD = atrioventricular (dual-chamber) implantable cardioverter-defibrillator.

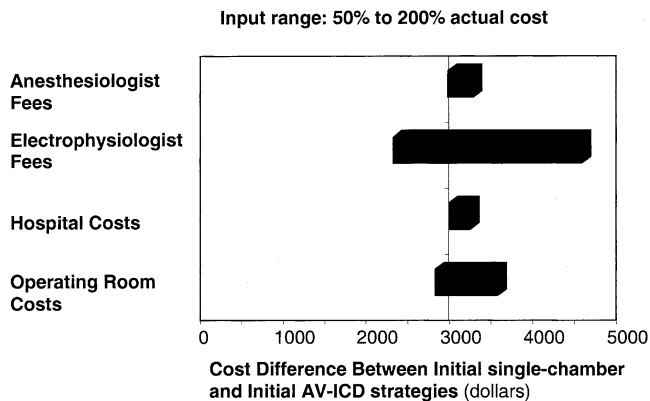


Figure 7. Sensitivity analysis, non-device costs. Input for each cost varied from 50% to 200% of baseline values. The x-axis represents the cost-advantage of the atrioventricular (dual-chamber) implantable cardioverter-defibrillator (AV-ICD) strategy over the single-chamber strategy. The vertical line represents the \$3,000 cost advantage of the AV-ICD strategy assuming baseline values. At no variation of input values does the AV-ICD strategy become more expensive (cross zero).

SENSITIVITY ANALYSIS: ATRIAL LEAD REPOSITIONING. Assuming an atrial lead repositioning rate of 4% (cost listed in Table 1), initial AV-ICD implantation remains the least expensive strategy. Sensitivity analysis reveals that an atrial lead repositioning rate of 61% would be needed to reverse the cost advantage of the AV-ICD.

DISCUSSION

The AV-ICD is a more expensive device than the single-chamber ICD; however, this decision analysis demonstrates that the strategy of universal AV-ICD implantation, regardless of clinical need or EPS results, is a dominant strategy that first, offers the benefits of dual-chamber capabilities for all patients and obviates the need for future upgrade, and second, does so at a lower cost to the health care system than would a strategy of initial implantation of the less-expensive single-chamber device. The cost advantage of the AV-ICD strategy was robust in the face of plausible uncertainty in upgrade rates, timing of upgrade, and other costs. Even at an upgrade as low as 5%, the universal AV-ICD strategy would remain the least expensive option if the cost difference between the single-chamber and AV devices was reduced to just \$1,568, roughly one-half of the current cost-difference. Ultimately, a reduction of the baseline cost of the AV-ICD by device manufacturers by this marginal amount could allow all patients to receive the AV-ICD at implant and obviate the need for future upgrade.

In our study, we describe the advantages of implanting dual-chamber hardware to preempt a later need for upgrade to dual-chamber pacing capabilities should the need for bradycardia pacing or supraventricular arrhythmia discrimination develop. Our results do not imply that devices be programmed for dual-chamber pacing. The recent Dual Chamber and VVI Implantable Defibrillator (DAVID) trial

(18) challenged the prior conventional wisdom that dual-chamber pacing is beneficial in patients with heart failure, demonstrating that right ventricular pacing can exacerbate CHF, presumably by creating asynchronous contraction with resultant impaired cardiac output (19). In the MOST study, for patients with pacemakers programmed DDD, heart failure hospital stays increased as percentage of ventricular pacing increased (20). Similarly, in the MADIT II study, patients receiving AV-ICDs were more likely to be hospitalized for heart failure than single-chamber recipients (21), although, because MADIT II was enrolling before publication of the DAVID trial, it is unlikely that efforts were made to avoid right ventricular pacing. Since the DAVID study, randomized trials have evaluated pacing modalities that allow atrial-based pacing while minimizing right ventricular pacing. For example, programming of the DDI/R mode can decrease ventricular pacing while providing “functional AAI/R pacing” for most patients (22). Recent innovations in device technology give further programming flexibility to decrease right ventricular pacing with a dual-chamber system. For example, one algorithm employing an atrioventricular search function has shown, in patients with a variety of baseline PR intervals, the ability to pace the atrium while pacing the right ventricle $\leq 3\%$ of the time (23,24). Thus, implantation of the dual-chamber device, through the option of atrial pacing, can decrease the likelihood of ventricular pacing exacerbations of CHF.

It is a limitation of our study that some upgrades were performed for CHF (with bradycardia or prolonged PR interval). This was a reasonable approach at the time of the study (1997 to 2001), but is now obsolete after the publication of the DAVID trial (18) and the availability of cardiac resynchronization therapy, which improves mortality (25) as well as symptoms (26) in patients with heart failure. To what extent the availability of this device, now 26% to 30% of ICDs implanted (industry data, Medtronic Inc., and Guidant Corp.), might impact the implications of our findings is unknown. Patients implanted with an AV-ICD who develop heart failure now would receive upgrade to a biventricular device, potentially offsetting an unknown fraction of the cost advantage of the strategy of universal AV-ICD implantation. Exclusion from our analysis of the patients who underwent upgrade for CHF, however, still leaves the upgrade rate higher than that demonstrated to show economic benefit from universal AV-ICD implantation. Whether there is a patient population for whom prophylactic implantation of a left ventricular lead would similarly result in lower total health care costs requires further clinical and economic analyses.

Since the end of our data collection, indications for ICDs have expanded on the basis of the results of MADIT II (4), which showed decreased mortality with the ICD in patients with a history of myocardial infarction and ejection fraction $\leq 30\%$, without EPS stratification, and the Sudden Cardiac Death in Heart Failure Trial (SCD-HeFT) (27), showing

mortality benefit of the ICD in those with New York Heart Association functional class II or III CHF and ejection fraction $\leq 35\%$. Whether later development of need for dual-chamber capability would be comparable in the MADIT II or SCD-HeFT populations to that which we observed is not known. In the current study, there were no differences in upgrade rates between those receiving ICDs for primary prophylaxis, as defined by MADIT and MUSTT, versus secondary prophylaxis. It is doubtful that the upgrade rates would differ considerably for MADIT II-type patients, because the differences in inclusion criteria between MADIT II and the previous primary prophylaxis trials—the absence of inducible ventricular tachycardia and lower ejection fraction—would be unlikely to lower the probability of development of atrial or bradyarrhythmias. Whether upgrade rates would be similar in the SCD-HeFT population, one-half of whom had non-ischemic cardiomyopathies, requires further study.

In the SCD-HeFT study, mortality benefit was seen with a single-lead device, and on the basis of this, the Center for Medicare and Medicaid Services has announced reimbursement of only these devices for patients receiving ICDs for primary prophylaxis unless medical need is documented (28). Detailed data from SCD-HeFT, however, such as occurrence of inappropriate shocks or need for atrial-based pacing, as would suggest benefit from AV-ICD, has not been reported. The current analysis suggests that further study in that population is needed regarding the medical and economic soundness of this policy.

Comparison with other studies. Previous studies have cited indications for AV-ICD implantation along with upgrade rates but have not evaluated costs associated with their use (12,17). The overall cost-effectiveness of the ICD is comparable to that of other life-saving therapies (29), but the costs of single-versus dual-chamber implantation were not evaluated. Other previous studies have reported predictive accuracies of EPS lower than those reported here. In these studies, the EPS performed poorly in documenting syncope caused by transient bradycardia (30–32). In contrast, we found that the EPS performed well in predicting the need for upgrade. Because a prolonged His ventricular interval might be an indicator of poor left ventricular function and sinus node disease might be associated with atrial arrhythmias, the ability of EPS to predict development of any cause for upgrade might be higher than the predictive accuracy for specific bradyarrhythmias.

Improved discrimination between ventricular and supraventricular arrhythmias, with presumed reduction in inappropriate shocks, was taken as indication for AV-ICD implantation, as it has been in other series (12,16), and as is deemed appropriate by recent ACC/AHA/NASPE guidelines (5). Large comparative studies of single-versus dual-chamber algorithms are lacking, however, and are difficult to perform given the number of devices and rapidly evolving

technologies. Retrospective comparisons suggest that dual-chamber algorithms discriminate supraventricular from ventricular tachycardias with higher sensitivity and specificity than do single-chamber algorithms (9,10). One prospective randomized study showed a decrease in inappropriate shocks with a dual-chamber algorithm in patients with a history of ventricular tachycardias ≤ 200 beats/min (33), whereas another, in an unselected population, did not (34). However, the percentage of patients receiving inappropriate shocks in both groups in the latter study was higher than in other series of dual-chamber devices (9,10). Improved dual-chamber tachycardia discrimination is a subject of active ongoing investigation (35,36).

Modeling limitations. Like all clinical policy models, our study is limited by the quality of its input data. We are mindful that our clinical data were obtained via a retrospective analysis in a single center. These data might not be applicable to decisions in other institutions and might even be inaccurate for setting policy. To date, however, there are no randomized trials comparing single-chamber devices to AV-ICDs or evaluating upgrade rates, which would provide more generalized data for purposes of decision support. Given the paucity of hard evidence in this area, it seems appropriate to examine threshold values and boundaries that might trigger a material change in decision making.

We are also mindful that we have assembled our economic input data from a variety of sources. Synthesis of cost data from diverse sources introduces the risk of mismatched estimates, reflecting different patient populations and significant differences in the costs of care from one geographic area to another. Here again, we have attempted to explore these possibilities via sensitivity analysis on each cost component. In general, we have found that our results are robust over plausible variation in the underlying cost data. Use of costs primarily from one center limits the direct generalizability to other centers; however, whereas reimbursements would not be center-specific, these might not reflect true resource use as accurately as do costs.

Some patients from the pre-AV-ICD group who underwent later upgrade might have had clinical indications for AV-ICD implantation, thus overestimating the positive predictive value of the EPS, and thus, the extrapolated upgrade rate. Sensitivity analyses, however, revealed the findings robust for much lower upgrade rates than our baseline estimate.

Conclusions. Although perhaps counterintuitive, the initial implantation of the more expensive dual-chamber device, which provides the benefits of dual-chamber capability while obviating any potential need for future upgrade, is the least costly overall strategy in most patient populations receiving ICDs. As indications for ICDs and the available technologies continue to expand, whether initial implantation of AV-ICDs will be the least expensive option in other populations requires further investigation.

Reprint requests and correspondence: Dr. Rachel Lampert, Yale University School of Medicine, Section of Cardiology, 333 Cedar Street, FMP 3, New Haven, Connecticut 06520. E-mail: rachel.lampert@yale.edu.

REFERENCES

1. Antiarrhythmics Versus Implantable Defibrillators (AVID) Investigators. A comparison of antiarrhythmic-drug therapy with implantable defibrillators in patients resuscitated from near-fatal ventricular arrhythmias. *N Engl J Med* 1997;337:1576–83.
2. Buxton A, Lee K, Fisher J, Josephson M, Prystowsky E, Hafley G. A randomized study of the prevention of sudden death in patients with coronary artery disease. *N Engl J Med* 1999;341:1882–90.
3. Moss A, Hall W, Cannom D, et al. Improved survival with an implanted defibrillator in patients with coronary disease at high risk for ventricular arrhythmia. *N Engl J Med* 1996;335:1933–40.
4. Moss AJ, Zareba W, Hall WJ, et al. Prophylactic implantation of a defibrillator in patients with myocardial infarction and reduced ejection fraction. *N Engl J Med* 2002;346:877–83.
5. Gregoratos G, Abrams J, Epstein AE, et al. ACC/AHA/NASPE 2002 guideline update for implantation of cardiac pacemakers and antiarrhythmia devices: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. Available at: www.acc.org/clinical/guidelines/pacemaker/pacemaker.pdf. Accessed July 7, 2005.
6. Higgins SL, Williams SK, Pak JP, Meyer DB. Indications for implantation of a dual-chamber pacemaker combined with an implantable cardioverter-defibrillator. *Am J Cardiol* 1998;81:1360–2.
7. Calkins H, Brinker J, Veltri EP, Guarnieri T, Levine JH. Clinical interactions between pacemakers and automatic implantable cardioverter-defibrillators. *J Am Coll Cardiol* 1990;16:666–73.
8. Epstein AE, Kay GN, Plumb VJ, Shepard RB, Kirklin JK. Combined automatic implantable cardioverter-defibrillator and pacemaker systems: implantation techniques and follow-up. *J Am Coll Cardiol* 1989;13:121–31.
9. Wilkoff BL, Kuhlkamp V, Volosin KJ, et al. Critical analysis of dual-chamber implantable cardioverter-defibrillator arrhythmia detection. *Circulation* 2001;103:381–6.
10. Swerdlow CD. Supraventricular tachycardia-ventricular tachycardia discrimination algorithms in implantable cardioverter-defibrillators. *J Cardiovasc Electrophysiol* 2001;12:606–12.
11. Karchmer AW, Longworth DL. Infections of intracardiac devices. *Cardiol Clin* 2003;21:253–71.
12. Higgins SL, Pak JP, Barone J, et al. The first year experience with the dual chamber ICD. *Pacing Clin Electrophysiol* 2000;23:18–25.
13. Gold MR, Siegel JE, Russel LB, Weinstein MC. Cost-effectiveness in health and medicine. Report of the Panel on Cost-effectiveness in Health and Medicine. New York, NY: Oxford University Press, 1996.
14. Josephson ME. Clinical Cardiac Electrophysiology: Techniques and Interpretations. 3rd edition. Philadelphia, PA: Lippincott, Williams, and Wilkins, 2002.
15. Lamas G, Lee KL, Sweeney MO, et al. Ventricular pacing or dual-chamber pacing for sinus node dysfunction. *N Engl J Med* 2002;346:1854–62.
16. Kuhlkamp V, Wilkoff BL, Brown AB, et al. Experience with a dual chamber implantable defibrillator. *Pacing Clin Electrophysiol* 2002; 25:1041–8.
17. Schoels W, Swerdlow CD, Jung W, Stein KM, Seidl K, Haffajee CJ. Worldwide experience with a new dual-chamber implantable cardioverter-defibrillator system. *J Cardiovasc Electrophysiol* 2001;12:521–8.
18. Wilkoff BL, Cook JR, Epstein AE, et al. Dual-chamber pacing or ventricular back-up pacing in patients with an implantable defibrillator: the dual-chamber or VVI implantable defibrillator (DAVID) trial. *JAMA* 2002;288:3115–23.
19. Harper GR, Pina IL, Kutalek SP. Intrinsic conduction maximizes cardiopulmonary performance in patients with dual chamber pacemakers. *Pacing Clin Electrophysiol* 1991;14:1787–91.
20. Sweeney MO, Hellkamp AS, Ellenbogen KA, et al. Adverse effect of ventricular pacing on heart failure and atrial fibrillation among patients with normal baseline QRS duration in a clinical trial of pacemaker therapy for sinus node dysfunction. *Circulation* 2003;107:2932–7.
21. Weiford BC, Vacek JL, Emert MP, et al. Effect of single-versus dual-chamber ICDs on heart failure and mortality in the MADIT II study (abstr). *Circulation* 2003;108:IV364.
22. Sweeney MO, Shea JB, Hellkamp AS. Effectiveness of DDI/R mode to minimize ventricular pacing in patients with dual chamber ICDs (abstr). *Heart Rhythm* 2004;1:S42.
23. Sweeney MO, Shea JB, Fox V, et al. Randomized pilot study of a new atrial-based minimal ventricular pacing mode in dual chamber implantable cardioverter-defibrillators. *Heart Rhythm* 2004;1:160–7.
24. Sweeney MO, Ellenbogen KA, Betzold R, et al. Multicenter, prospective, randomized trial of a new atrial-based managed ventricular pacing mode (MVP) in dual chamber ICDs (abstr). *Circulation* 2004;110: III444.
25. Bristow MR, Saxon LA, Boehmer J, et al. Cardiac-resynchronization therapy with or without an implantable cardioverter-defibrillator in advanced chronic heart failure. *N Engl J Med* 2004;350:2140–50.
26. Cazeau S, Leclercq C, Lavergne T, et al. Effects of multisite biventricular pacing in patients with heart failure and intraventricular conduction delay. *N Engl J Med* 2001;344:873–80.
27. Bardy GH, Lee KL, Mark DB, et al. Amiodarone or an implantable cardioverter-defibrillator for congestive heart failure. *N Engl J Med* 2005;352:225–37.
28. Center for Medicare and Medicaid Services. Available at: www.cms.hhs.gov/mcd/viewdecisionmemo.asp?id=148. Accessed July 7, 2005.
29. Jauhar S, Slotwimer DJ. The economics of ICDs. *N Engl J Med* 2005;352:225–4.
30. Fujimura O, Yee R, Klein G, Sharma AD, Boahene KA. The diagnostic sensitivity of electrophysiology testing in patients with syncope caused by transient bradycardia. *N Engl J Med* 1989;321: 1703–7.
31. DiMarco JP, Garan H, Harthorne JW, Ruskin JN. Intracardiac electrophysiologic techniques in recurrent syncope of unknown cause. *Ann Intern Med* 1981;95:542–8.
32. Hess DS, Morady F, Scheinman MM. Electrophysiologic testing in the evaluation of patients with syncope of undetermined origin. *Am J Cardiol* 1982;50:1309–15.
33. Bänsch D, Steffgen F, Grönefeld G, et al. The 1+1 trial: a prospective trial of a dual- versus a single-chamber implantable defibrillator in patients with slow ventricular tachycardias. *Circulation* 2002;110: 1022–9.
34. Theuns DAMJ, Klootwijk PJ, Goedhart DK, Jordaens LJLM. Prevention of inappropriate therapy in implantable cardioverter-defibrillators. *J Am Coll Cardiol* 2004;44:2362–7.
35. Lee MA, Corbisiero R, Nabert DR, et al. Clinical results of an advanced supraventricular tachycardia detection enhancement algorithm (abstr). *Heart Rhythm* 2004;1:S114.
36. Atienza F, Almendral J, Garcia J, et al. A new step-wise approach to implantable cardioverter-defibrillator electrograms tachycardia discrimination (abstr). *J Am Coll Cardiol* 2005;45 Suppl A:104A.